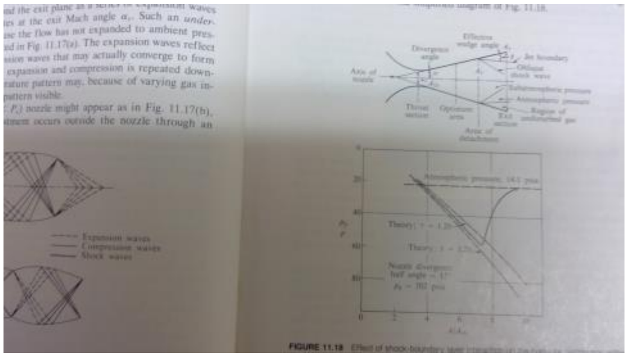

nd the exit plane as a series of expansion waves
es at the exit Mach angle α_e. Such an *under-*
se the flow has not expanded to ambient pres-
ed in Fig. 11.17(a). The expansion waves reflect
sion waves that may actually converge to form
expansion and compression is repeated down-
rature pattern may, because of varying gas in-
pattern visible.
P_a) nozzle might appear as in Fig. 11.17(b),
stment occurs outside the nozzle through an

FIGURE 11.18 Effect of shock-boundary-layer interaction...

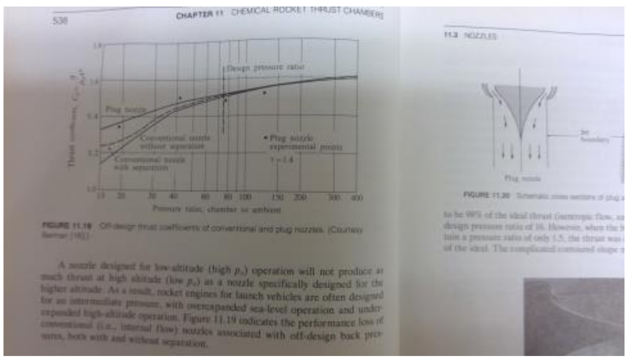
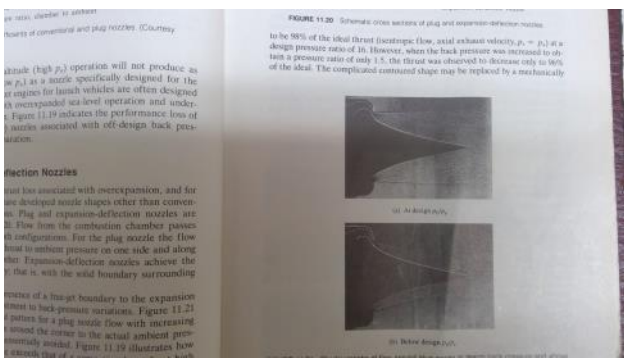


FIGURE 11.19 Off-design thrust coefficients of conventional and plug nozzles. (Courtesy Berman [18].)

A nozzle designed for low-altitude (high p_a) operation will not produce as much thrust at high altitude (low p_a) as a nozzle specifically designed for the higher altitude. As a result, rocket engines for launch vehicles are often designed for an intermediate pressure, with overexpanded sea-level operation and underexpanded high-altitude operation. Figure 11.19 indicates the performance loss of conventional (i.e., internal flow) nozzles associated with off-design back pressures, both with and without separation.

FIGURE 11.20 Schematic cross sections of plug a...


ficients of conventional and plug nozzles. (Courtesy

titude (high p_a) operation will not produce as
w p_a) as a nozzle specifically designed for the
et engines for launch vehicles are often designed
th overexpanded sea-level operation and under-
. Figure 11.19 indicates the performance loss of
) nozzles associated with off-design back pres-
aration.

flection Nozzles

rust loss associated with overexpansion, and for
ave developed nozzle shapes other than conven-
s. Plug and expansion-deflection nozzles are
0. Flow from the combustion chamber passes
th configurations. For the plug nozzle the flow
hroat to ambient pressure on one side and along
her. Expansion-deflection nozzles achieve the
y; that is, with the solid boundary surrounding

resence of a free-jet boundary to the expansion
stment to back-pressure variations. Figure 11.21
 pattern for a plug nozzle flow with increasing
 around the corner to the actual ambient pres-
entially avoided. Figure 11.19 illustrates how

FIGURE 11.20 Schematic cross sections of plug and expansion-deflection nozzles.

to be 98% of the ideal thrust (isentropic flow, axial exhaust velocity, $p_e = p_a$) at a design pressure ratio of 16. However, when the back pressure was increased to obtain a pressure ratio of only 1.5, the thrust was observed to decrease only to 96% of the ideal. The complicated contoured shape may be replaced by a mechanically

(a) At design p_c/p_a

(b) Below design p_c/p_a

$$\left(\quad \right)$$

For $\left(\frac{p_0}{p_a}\right)_{act} < \left(\frac{p_0}{p_a}\right)$

in the nozzle.

For $\left(\frac{p_0}{p_a}\right)_{act} > \left(\frac{\quad}{\quad}\right)$, flow supersonic in the